AN ELECTRIC HIGH VOLTAGE AC MACHINE

The present invention relates to an electric high voltage AC machine intended to be directly connected to a distribution or transmission network, said machine comprising at least one winding.

Such generators with a rated voltage of up to 36 kV is described by Paul R. Siedler, "36 kV Generators Arise from Insulation Research", Electrical World, October 15, 1932, pp. 524-527. These generators comprise windings formed of medium voltage insulated conductors wherein insulation is subdivided into various layers of different dielectric constants. The insulating material used is formed of various combinations of the three components of micafolium-mica, varnish and paper.

In a publication by Power Research Institute, EPRI, EL-3391, April 1984 a generator concept is proposed for providing such high voltages that the generator can be directly connected to a power network without any intermediate transformer. Such a generator was supposed to comprise a superconducting rotor. The magnetization capacity of the superconducting field would then make it possible to use air gap windings of sufficient thickness for withstanding the electric forces. The proposed rotor is, however, of a complicated structure with a very thick insulation which considerably increases the size of the machine. In addition thereto special measures have to be taken for insulating and cooling the coil end sections.

By electric high voltage AC machines is meant, according to the present invention, rotating electric machines like generators in power stations for production of electric power, double-fed machines, outer pole machines, synchronous machines, asynchronous converter cascades, as well as power transformers. For connecting such machines, except for transformers, to distribution and transmission networks, in the following commonly

referred to as power networks, a transformer has so far been needed for transforming the voltage up to the network level, that is in the range of 130-400 kV.

By manufacturing the winding of these machines of an insulated electric high voltage conductor with a solid insulation of similar structure as cables used for power transmission the voltage of the machine can be increased to such levels that the machines can be directly connected to any power network without an intermediate transformer. Thus this transformer can be omitted. Typical working range for these machines is 30-800 kV.

For this kind of machines special attention has to be paid to grounding problems.

Grounding of generator systems and other similar electrical systems implies intentional measures for connecting an electric system to ground potential. When the so-called neutral point of the system is available it is often connected to ground, directly or through a suitable impedance. It also happens that other points in the system are connected to ground. If one point in the system is grounded the complete system is grounded as long as the galvanic connection extends.

The grounding principle used is determined by the design of the system. For a system including a generator directly connected to a Y-Δ connected step-up-transformer with the Δ-winding at the generator voltage the following grounding alternatives are most common.

- High resistance grounding
- No grounding
- Resonant grounding.

High resistance grounding is normally realized by connection of a low ohmic resistor in the secondary of a distribution transformer with the primary winding of the transformer connected from the generator neutral point to ground. Such prior art grounding is illustrated in fig. 1, which shows a generator 2 connected by a Y-Δ connected step-up transformer 3 to a network 9. The primary 11 of a

distribution transformer is connected between the neutral point of the generator 2 and ground. In the secondary 10 of the transformer a resistor 12 is connected.

The same kind of grounding can, of course, be obtained by installing a high ohmic resistor directly between the generator neutral point and ground.

An ungrounded electric system lacks any intentional connection to ground. Thus an ungrounded generator has no connection between its neutral point and ground, except for possible voltage transformers for feeding different relays and instruments.

Resonant grounding is normally also realized as illustrated in fig. 1 with the resistor 12 replaced by a reactor 12a. The reactor reactance is chosen such that the capacitive current during a line to ground fault is neutralized by an equal component of inductive current contributed for by the reactor 12a.

Also low resistance or low impedance grounding and effective grounding of the above systems are possible. Low resistance or low impedance grounding will result in lower transient overvoltages but higher ground fault currents, which can cause internal damages to the machine.

Low resistance grounding is achieved by the intentional insertion of a resistance between the generator neutral and ground. The resistance may be inserted either directly in connection to ground or indirectly, in the secondary of a transformer whose primary is connected between generator neutral and ground, cf. fig. 1.

Low impedance grounding, that is low inductance grounding is accomplished in the same way as low resistance grounding with the substitution of an inductor for the resistor. The value of the inductor in ohms is less than that required for resonant grounding, as discussed above.

For systems comprising several generators connected to a common feeding line or bus with circuit breakers between the generator terminals and the common bus low resistance or low impedance grounding is suitable.

Effectively grounding the neutral of a generator has substantially the same advantages and disadvantages as the low resistance or low impedance grounding with some differences.

A system is said to be effectively grounded if certain impedance requirements, which restricts the size of the grounding impedance, are fulfilled. In an effectively grounded system the maximum phase-to-ground voltage in unfaulted phases, in case of a ground fault, are limited to 80% of phase-to-phase voltage.

A power system network is mainly grounded through ground connections of neutral points of transformers in the system and can include no impedance (except for contact resistances), so-called direct grounding, or have a certain impedance.

Previously known grounding techniques are described in e.g. the publication IEEE C62.92-1989, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part II - Grounding of Synchronous Systems, published by the Institute of Electrical and Electronics Engineers, New York, USA, September, 1989.

If the generator neutral is grounded through a low resistance or inductance as discussed above, a path is formed for third harmonic currents from the generator neutral to ground. If a directly grounded or low-impedance grounded transformer winding or another low-impedance grounded generator is directly connected to the generator, the third harmonic currents will circulate therebetween under normal conditions.

Techniques for solving the problems of third harmonic currents in generator- and motor-operation of AC electric machines of the kind to which the present invention relates are described in Swedish patent applications 9602078-9 and 9700347-9.

The purpose of the present invention is to provide an electric high voltage AC machine suitable for direct connection to distribution or transmission networks as indicated above, which machine is provided with grounding

means suitable for different uses and operating conditions of the machine.

Sub D4

This purpose is obtained with an electric high voltage AC machine of the kind defined in the introductory portion of the description and having the characterising features of claim 1.

An important advantage of the machine according to the invention resides in the fact that the electric field is nearly equal to zero in the end region of the windings outside the second layer with semiconducting properties. Thus no electric fields need to be controlled outside the winding and no field concentrations can be formed, neither within the sheet, nor in winding end regions, nor in transitions therebetween.

According to an advantageous embodiment of the machine according to the invention at least two adjacent layers have substantially equal thermal expansion coefficients. In this way defects, cracks or the like as a result of thermal motions in the winding, are avoided.

According to another advantageous embodiment of the machine according to the invention said grounding means comprise means for low resistance grounding of the winding. In this way transient overvoltages as well as the ground fault current can be limited to moderate values.

According to still another advantageous embodiment of the machine according to the invention, wherein the machine has a Y-connected winding, the neutral point of which being available, high resistance grounding means comprise a resistor connected in the secondary of a transformer whose primary is connected between the neutral point and ground. In this way the resistor used in the secondary of the transformer is of comparatively low ohmic value and of rugged construction. Sufficient damping to reduce transient overvoltages to safe levels can be achieved with a properly sized resistor. Further, mechanical stresses and fault damages are limited during line-to-ground faults by the restriction of the fault current. Such a grounding device is also more economical

than direct insertion of a high ohmic resistor between the generator neutral and ground.

According to another advantageous embodiment of the machine according to the invention, wherein the machine has a Y-connected winding the neutral point of which being available, the grounding means comprises a reactor connected in the secondary of a transformer whose primary is connected between the neutral point and ground, said reactor having characteristics such that the capacitive current during a ground fault is substantially neutralized by an equal component of inductive current contributed for by the reactor. In this way the net fault current is reduced to a low value by the parallel resonant circuit thus formed, and the current is essentially in phase with the fault voltage. The voltage recovery on the faulted phase is very slow in this case and accordingly any ground fault of a transient nature will automatically be extinguished in a resonant grounded system.

According to still other advantageous embodiments of the machine according to the invention the grounding means comprise a Y-Δ grounding transformer or a so-called zigzag grounding transformer connected to the network side of the machine. The use of such grounding transformers are equivalent to low inductance or low resistance grounding with respect to fault current levels and transient overvoltages.

To explain the invention in more detail embodiments of the machine according to the invention, chosen as examples, will now be described more in detail with reference to fig. 2-11 on the accompanying drawings on which

fig. 1 illustrates prior art grounding of a synchronous generator,

fig. 2 shows an example of the insulated conductor used in the windings of the machine according to the invention,

fig. 3 shows an ungrounded three-phase machine in the form of a Y-connected generator or motor connected to a power system,

figs. 4-13 show different examples of grounding the Y-connected machine in fig. 3,

fig. 14 shows a machine according to the invention in the form of a Δ-connected generator or motor connected to a power system, and

fig. 15 illustrates the use of a grounding transformer in the system shown in fig. 14.

In fig. 2 an example is shown of an insulated conductor, which can be used in the windings of the machine according to the invention. Such an insulated conductor comprises at least one conductor 4 composed of a number of non-insulated and possibly insulated strands 5. Around the conductor 4 there is an inner semiconducting layer 6, which is in contact with at least some of the non-insulated strands 5. This semiconducting layer 6 is in its turn surrounded by the main insulation of the cable in the form of an extruded solid insulating layer 7. The insulating layer is surrounded by an external semiconducting layer 8. The conductor area of the cable can vary between 80 and 3000 mm^2 and the external diameter of the cable between 20 and 250 mm.

Fig. 3 shows schematically an ungrounded electric high voltage AC machine in the form of a Y-connected generator or motor 14 directly connected to a power system 16.

Fig. 4 shows grounding means in the form of an overvoltage protector, like a non-linear resistance arrester 18, connected between the neutral point 20 of the Y-connected machine 14 and ground. Such a non-linear resistance arrester 18 connected to the neutral point protects the insulated conductor used in the machine windings against transient overvoltages, such as overvoltages caused by a stroke of lightning.

Fig. 5 shows an embodiment with a high ohmic resistor 22 connected in parallel to the non-linear resistance arrester 18. The non-linear resistance arrester 18 is functioning in the same way in this embodiment as in the embodiment shown in fig. 4 and with

the resistor 22 a sensitive detection of ground faults by measuring the voltage across the resistor 22 is realised.

Fig. 6 shows an embodiment with high resistance grounding of the neutral point 20. In this embodiment a technique similar to the prior art described in connection with fig. 1 is used. Thus a resistor 24 is connected to the secondary 26 of a transformer with the primary winding 28 of the transformer connected from the neutral point 20 of the machine 14 to ground. The resistor 24 is comparatively low ohmic and of rugged construction, as compared to a high ohmic resistor which would be needed for direct connection between the neutral point 20 and ground for obtaining the same result. The voltage class of the resistor can consequently be reduced. Also in this case a non-linear resistance arrester 18 is connected in parallel to the primary winding 28. With this embodiment mechanical stresses and fault damages are limited during line-to-ground faults by restricting the fault current. Transient overvoltages are limited to safe levels and the grounding device is more economical than direct insertion of a resistor.

Resonant grounding of the machine can be realised in a similar way by replacing the resistor 24 by a reactor having characteristics such that the capacitive current during a line-to-ground fault is neutralized by an equal component of inductive current contributed for by the reactor. Thus the net fault current is reduced by the parallel resonant circuit thus formed and the current will be essentially in phase with the fault voltage. After extinction of the fault the voltage recovery on the faulted phase will be very slow and determined by the ratio of inductive reactance to the effective resistance of the transformer/reactor combination. Accordingly any ground fault of transient nature will automatically be extinguished in such a resonant grounded system. Thus such resonant grounding means limits the ground fault current to practically zero, thus minimising the mechanical stresses. Further continued operation of the machine can

be permitted after the occurrence of a phase-to-ground fault until an orderly shutdown can be arranged.

Fig. 7 shows an embodiment with a non-linear resistance arrester 18 connected between the neutral point 20 and ground and a grounding transformer 30 connected on the network side of the machine 14. The grounding transformer 30 is of Y-Δ design with the neutral point of the Y-connection connected to ground, whereas the Δ-winding is isolated. Grounding transformers are normally used in systems which are ungrounded or which have a high impedance ground connection. As a system component the grounding transformer carries no load and does not affect the normal system behaviour. When unbalances occur the grounding transformer provides a low impedance in the zero sequence network. The grounding transformer is in this way equivalent to a low inductance or low resistance grounding with respect to fault current levels and transient overvoltages.

The grounding transformer can also be a so-called zigzag transformer with special winding arrangements, see e.g. Paul M. Anderson, "Analysis of Faulted Power Systems", The Iowa State University Press/Ames, 1983, pp. 255-257.

Also a possible auxiliary power transformer can be used for such grounding purposes.

Fig. 8 shows an embodiment with a low ohmic resistor 32 connected between the neutral point 20 of the machine 14 and ground. The main advantage of such a low resistance grounding is the ability to limit transient and temporary overvoltages. The currents will, however, be higher in case of single phase ground faults. Also third harmonic currents will be higher in undisturbed operation.

Fig. 9 shows an alternative embodiment of the machine according to the invention in which the resistor 32 is replaced by a low inductance inductor 34 connected between the neutral point 20 and ground. Low inductance grounding works essentially in the same way as low ohmic grounding. The value of the inductor 34 in ohms is less

than that required for resonant grounding, cf. description of fig. 6.

As an alternative to the direct connection between the neutral point 20 and ground of the resistor 32 or the inductor 34, they may be indirectly connected with the aid of a transformer whose primary is connected between the neutral point 20 and ground and whose secondary contains the resistor or inductor, cf. the description of fig. 6.

In fig. 10 an embodiment is shown comprising two impedances 36 and 38 connected in series between the neutral point 20 of the machine 14 and ground, the impedance 36 having a low impedance value and the impedance 38 a high impedance value. The impedance 38 can be short-circuited by a short-circuiting device 40. In normal operation the short-circuiting device 40 is open in order to minimize third harmonic currents. In case of a ground fault the short-circuiting device 40 is controlled to short-circuit the impedance 38 and the potential in the neutral point 20 will be low and the current to ground comparatively high.

In case of an internal ground fault in the machine 14 the impedance 38 is not short-circuited. As a consequence the voltage will be high in the neutral point 20 but the current to ground will be limited. In such a situation this is to prefer since a high current can give rise to damages in this case.

To be able to cope with the problems arising from third harmonics when directly connecting an AC electric machine to a three-phase power network, i.e. when no step-up transformer is used between the machine and the network, grounding means in the form of a suppression filter 35, 37, tuned to the third harmonic together with an overvoltage protector 39 can be used, see fig. 11. The filter thus comprises a parallel resonance circuit consisting of an inductor 35 and a capacitive reactance 37. The dimensioning of the filter 35, 37 and its overvoltage protector 39 is such that the parallel circuit is capable of absorbing third harmonics from the machine

14 during normal operation, yet limiting transient and temporary overvoltages. In case of a fault the overvoltage protector 39 will limit the fault voltage such that the fault current flows through the overvoltage protector 39 if the fault is considerable. In case of a single-phase ground fault the currents will be higher as compared to e.g. the case of high resistance grounding since the fundamental impedance is low.

In fig. 12 an embodiment is shown wherein the grounding means comprises a detuned switchable third harmonics depression filter connected in parallel to an overvoltage protector 40. Such filters can be realised in several different ways. Fig. 12 shows an example comprising two inductors 42, 44 connected in series and a capacitor 46 connected in parallel to the series-connected inductors 42, 44. Further a short-circuiting device 48 is connected across the inductor 44.

The short-circuiting device 48 is controllable to change the characteristic of the filter by short-circuiting the inductor 44 when a risk for third harmonic resonance between the filter and the machine 14 and network 16 is detected. This is described more in detail in Swedish patent application 9700347-9. In this way third harmonic currents are strongly limited in normal operation. Transient and temporary overvoltages will be limited and the currents will be higher in case of a single-phase ground fault in the same way as described in connection with fig. 11.

Fig. 13 shows an embodiment wherein the neutral point 20 of the machine 14 is directly connected to ground, at 21. Such direct grounding limits transient and temporary overvoltages but results in high currents in case of ground faults. Third harmonic current flow from the neutral 20 of the machine to ground will be comparatively high in normal operation.

As a further alternative the grounding means of the machine according to the invention can comprise an active

circuit for providing a connection of the neutral point to ground having desirable impedance properties.

In fig. 14 a Δ-connected three-phase machine 50 is shown directly connected to the distribution or transmission network 16.

In such a situation a grounding transformer of the same kind as the one used in the embodiment shown in fig. 7 can be connected on the network side of the machine 50.

As in the embodiment of fig. 7 the grounding transformer can be a Y-Δ-connected transformer with the neutral point of the Y-connection ground, or a so called zigzag grounding transformer, that is a Z-0-connected transformer with the Z grounded. The grounding transformer will limit temporary overvoltages.

As in the embodiment of fig. 7 a possible auxiliary power transformer can also be used for this purpose.